Models for the description of man-machine interaction for the tasks of computer-aided assessment of the reliability of automated systems

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***Abstract*— The task of functional network description formalization for operator activity algorithm in automated systems is examined. The method of functional networks description is developed. The results can be used to organize the design of human-machine interaction. The models provide a convenient dialogue between the designer and the computer system of the ergonomic support of automated systems. The technology of automatic structural analysis and assessment of the reliability of a human operator is shown.**

***Keywords*— automated system, ergonomics, reliability, human factor, computer modeling, man-machine, interaction, algorithm of functioning, functional network**

I. Introduction

The effectiveness of automated systems depends significantly on the consideration of the so-called "human factor" [1–6].

Creation of a scientific school "The effectiveness, quality and reliability of systems "man – technology – environment" by Professor Gubinsky A.I. was, in fact, a revolution in ergonomics, which allowed to find approaches to the formalization and optimization of the human-operator's actions [7–9].

The functional network (FN) specifies the activity of the human-operator [7–9], but there are big problems associated with the convenience of entering the structure of this FN into the computer for subsequent simulation of human-machine interaction.

II. Statement of the Task

FN is used by many authors to model human activities and assess risks in different systems:

- in information processing systems [7, 10–12];
- in the systems of computer production management and decision support systems [7, 9, 10, 13–17];
- in e-learning systems [7, 10, 18–20];
- in space systems [7, 8].

The FN is a very convenient model, because it allows you [7–10, 21]:

- to describe human activities and computer operations;
- to assess the accuracy and implementation time of activities;
- to set and solve optimization problems.

FN is more convenient than Petri networks [7, 22] and other network models, because it allows you not only to describe the process but also to evaluate it.

However, in order to evaluate the FN indicators, it is necessary to "collapse", i.e. carry out a reduction. To do this, one should be able to recognize typical blocks of operations in the description, and then – to change them by one operation with equivalent characteristics.

Until today, this was done manually. Unfortunately, so far we have not been able to automate the folding procedure.

The main problem is the recognition of typical blocks of operations.

Disadvantages of manual recognition:

- great labor intensity;
- errors of recognition;
- high time consumption.

However, this is unacceptable when the management tasks in complex systems are being solved [1–6, 23].

In connection with these problems, we define the task. The purpose of this work is to create an approach to the development of a language describing FN, which allows you:

– to describe FN (in a form convenient for input into the computer), including:

- operations algorithm – typical functional units (TFU);
- communication between operations (TFU);
- characteristics of operations;
- typical blocks of operations – type functional structures (TFS);
- rules for identifying TFS;
- rules for converting (reducing) FN;
- models for calculating the indicators at the steps of reduction;

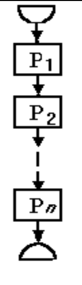
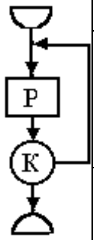
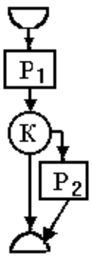
– to provide automatic reduction and evaluation of FN indicators.

III. Results

A. *Principle of description and assessment of typical functional structures for tasks of evaluation for human-machine dialogue electing a Template*

Simulation of elementary actions of operators and automatics is carried out using TFU. The most common of these are the "work operation" with the designation "rectangle", "control operation" with the designation "circle", and "alternative operation" with the designation "rectangle with several outputs". A complete description of TFU models is given in [7–9]. The FN that describes the algorithmic activity of the human operator is built from those TFU. Examples of models (accuracy and run-time estimation) for TFS are shown in Table I.

TABLE I. Examples of typical functional structures*

Content of typical functional structure	TFS diagram	Index	Formula for computation
1.Consistent implementation of operations		Probability of error-free operation	$B = \prod_{i=1}^{n} B_i$
		Expectation value of the time of operation	$M(T) = \sum_{i=1}^{n} M(T_i)$
		Dispersion of the time of operation	$D(T) = \sum_{i=1}^{n} D(T_i)$
2.Cyclic functional structure "An operation with action control without restrictions on the number of cycles"		Probability of error-free operation	$B = B^1 * K^{11} * \frac{1}{1-(B^1 * K^{10} + B^0 * K^{00})}$
		Expectation value of the time of operation	$M(T) = (M(T_p) + M(T_к)) * M(L)$ $M(L) = \frac{1}{1-(B^1 * K^{10} + B^0 * K^{00})}$
		Dispersion of the time of operation	$D(T) = D(T) * (M(T_p) + M(T_к))^2 + (D(T_p) + D(T_к)) * M(L)$ $D(L) = \frac{B^1 * K^{10} + B^0 * K^{00}}{(1-(B^1 * K^{10} + B^0 * K^{00}))^2}$
3. Functional structure "An operation with action control and without restrictions on the number of cycles"		Expectation value of the time of operation	$B = B_1^1 * K^{11} + (B_1^0 * K^{00} + B_1^1 * K^{10}) * B_2^1$
		Expectation value of the time of operation	$M(T) = M(T_{p1}) + M(T_к) + (B_1^0 * K^{00} + B_1^1 * K^{10}) * M(T_{p2})$
		Dispersion of the time of operation	$D(T) = D(T_{p1}) + D(T_к) + (B_1^0 * K^{00} + B_1^1 * K^{10}) * D(T_{p2}) + (B_1^0 * K^{00} + B_1^1 * K^{10}) * (B_1^1 * K^{11} + B_1^0 * K^{01}) * M^2(T_{p2})$

a. * - Subscripts in formulas correspond to the type (operating course – p; course of control – k) and / or to the number of TFU.

Here:

B^1 – the probability of error-free handling operation;

K^{11} – the probability of recognizing the correct operations performing;

K^{00} – the probability of detecting any errors;

M(T) – mathematical expectation of the operational run-time;

D(T) – the variance of the operational run-time.

These models are used to evaluate the entire FN. The estimation is carried out by the method of folding (reduction) FN [8, 10].

B. *Development of models for the describtion and evaluation of FN in general*

By a formalized description of a functional network, we mean the representation of the algorithm for the functioning of the human machine system (HMS) by a structural formula consisting of two sets of elements – M_1 and M_2:

M_1 – a set of elements of the FN description, with the help of which a functional network description of the activity algorithm is constructed taking into account events, the detection and elimination of errors (including various types);

M_2 – a set of links (description operations) between elements of the FN description. This is a set of relations between the elements of the particular FN description (order, outputs and transitions).

Then we obtain an FN description model in a general form:

$$O_{FS} ::=< E_{FS}, S_{FS} >, \qquad (1)$$

where: E_{FS} – a subset of description elements from the set M_1, $E_{FS} \in$ M1;

S_{FS} – a subset of operations describing the set M_2, $S_{FS} \in M_2$.

Estimation of the functional network process is also given by elements of two sets M_3 and M_4:

M_3 – a set of assessment elements; probabilistic and cost characteristics, which are used to evaluate the performance of the elements of the FN description;

M_4 – a set of evaluation operations, that is, operations on the evaluation elements, with the help of which the probability-time characteristics of the whole HMS operation algorithm are calculated.

The M_4 set includes the library of well-known mathematical models for calculating the performance indicators of typical functional structures and replacing them with equivalent standard functional units, taking into account one error, and developed models for accounting for errors of different types.

We introduce a one-to-one correspondence: first, between the description elements of M_1 and the estimation elements from M_3; secondly, between the description operations of M_2 and the estimation operations from M_4. This allows one to quantify the algorithm of HMS operation using a formal procedure: it suffices to describe the operation algorithm using the M_1 and M_2 sets, and then identify and replace each description operation from the M_2 set with the corresponding estimated operation from the M_4 set.

The procedure for replacing the description operations with their estimated analogs in the study of a formalized FN will be called the folding or FN reduction (by analogy with the FN graphical representation reduction). This procedure is based on the use of typical functional units and structures. Then, we get an estimate of the FN model in general:

$$C_{FS} = < C_{EFS}, C_{OFS}, \Pr_{FS} >, \qquad (2)$$

where: C_{EFS} – a subset of assessment elements from the set M_3, $C_{EFS} \in M_3$;

C_{OFS} – a subset of evaluation operations from the set M_4, $C_{OFS} \in M_4$;

Pr_{FS} – reduction protocol of the FN model.

Determine the values of the description elements, evaluation elements and description operations used to represent the functional network and other objects.

C. FN elements description

With the help of the description elements (given elements M1), the notation TFU (the functionaries of the main and supplementary and compilers of auxiliary and service), the name TFU and the equivalent name TFU in the structure of the activity algorithm are indicated. The functionaries correspond to the real operations or actions of a person, the operations of technological equipment, computer equipment and software in the analyzed algorithm of functioning, and composers correspond to certain interrelations of operations and logical functions.

The designations of the functioning of some units, taken to designate the elements of FN, their names are given in Table II.

TABLE II. THE DESCRIPTION ELEMENTS FOR DESIGNATION OF THE FUNCTIONING BASIC TYPICAL UNITS

Number	**Description element definition**	**Application for description**
1	R	Working operation
2	A	Alternative operation
3	K	Operation control function
4	Z	Delay operation

As descriptive elements to indicate the name of the TFU and the equivalent TFU in the structure of the activity algorithm, we will use character sequences that indicate the type of TFU or the equivalent TFU and the number of this TFU in the structure of the algorithm:

«*P1*», «*P2*»,…, «*Pn*», «*K1*», «*K2*»,…, «*Pe1*»,… .

D. A set of evaluation elements

Elements of this group are used as variables for setting values of quality indicators of descriptive elements from the set M_1. A variable, like in mathematics, is an object with the name and meaning. The name is used to indicate the quality score. The variable gets a specific value in the process of setting the value to the evaluation elements (elements of the set M_3), i.e. probabilistic and temporal characteristics, with the help of which the quality of descriptive elements performance is evaluated.

Examples of variables and their use are shown in Table III.

TABLE III. EVALUATION ELEMENTS

Number	**Evaluation element designation**	**Application for setting values**
1	B^1	TFU error-free execution probability
2	B^0	TFU erroneous execution probability
5	M_T	Expected value of execution time
6	D_T	Execution time dispersion
7	K^{11}	The conditional probability that the operation being tested, if it is actually performed correctly, will be recognized as correct.
8	K^{00}	The conditional probability that the operation being checked, if it is actually performed incorrectly, will be considered invalid

E. TFU Model

A formalized description of the functional unit is an element of the description from the set M_1, together with the corresponding elements of the evaluation from the set M_3.

Then the *i*-th model functional unit will look like:

$$Fe_i ::= < o_{e_i}, \{c_{e_{ij}}\} \big| j = 1,2,..m_i >, o_{e_i} \in M_1, c_{e_{ij}} \in M_3 \qquad (3)$$

where: Oe_i – the *i*-th description element of the set M_1;

Ce_{ij} – *j*-th evaluation element (*j*-th quality indicator) of the *i*-th item from the set M_3;

m_i – the number of evaluation elements related to the *i*-th descriptive element.

Using the resulting model of functional units in general form (formula 3), as well as the elements of description and evaluation defined above, we describe some functional units (Table IV).

TABLE IV. THE FUNCTIONAL UNITS' DESCRIPTION

TFU number	**TFU contents**	**TFU model**
1	Working	$Fe_1=<R,B^1,B0,[M_T,D_T],[M_C,D_C],[M_W,D_W]>$
2	Alternative	$Fe_2=<A,A_i,A_{ij},[M_T,D_T],[M_C,D_C],[M_W,D_W]>$
3	Function monitoring	$Fe_3=<K,K^{11},K^{10},K^{00},K^{01},[M_T,D_T],[M_C,D_C],[M_W,D_W]>$
4	Delay	$Fe_4=<Z,[M_T,D_T],[M_C,D_C],[M_W,D_W]>$

F. The description of relationships between FN elements

The connections between the FN elements are specified by the elements of the set M_2, that map how connected and in which sequence the operation units are performed. Elements of this group are generally denoted by N_j, V_{jl}, L_{jl} variables with lower indices, used in models to define relationships between functional structures elements and a functional network, and take integer values. We use of these variables:

N_j – the serial TFU number in the algorithm structure;

V_{jl} – the transition possible type after the TFU execution with the number N_j;

L_{jl} – TFU number executed after the TFU execution with the number N_j, if a type transition occurs V_{jl}. The list of transitions possible types and the corresponding values of the variable V_{jl} are given in Table V.

TABLE V. APPLICATION OF THE VARIABLE VJL

Variable value Vj_l	Use to specify the transition type
1	The transition to TFU in the structure of the algorithm following the given in the main algorithm direction
2	Transition to the TFU, which follows the current TFU "operation control" in case of operation erroneous execution
3	Transition to the TFU following the current TFU "performance check" in case of operation erroneous execution
4	Transition to the TFU of the continuation of the cycle following the current TFU
5	The transition to the TFU, which follows the current TFU and signifies the exit from the cycle

In the elements group of the links assignment we add the variable *kc*, which means the restriction on the number of repetitions in the cycle.

G. TFS Model

A functional structure formalized description is a description operation from the set M_2 that defines the relations between several description elements, together with the corresponding valuation operations from the set M_4. Then, the *i*-th model functional structure will look like:

$$Fs_i ::=<\{o_{e_{ij}}, N_{ij}, \{V_{ij_l}, L_{ij_l}\} \Big| l=1,2,..\eta_{ij}, [k_{c_j}]\} \Big| j=1,2,..k_i\}, o_{ee_i}, \{y_{i_m}\} \Big| m=1,2,..z_i> \quad (4)$$

where: Oe_{ij} – *j*-th description element of the *i*-th functional structure;

k_i – number of description elements of the *i*-th functional structure;

k_{cj}– restriction on the repetitions number in a cycle;

$\{N_{ij}, \{V_{ijl}, L_{ijl}\} | l=1,2,...,\eta_{ij}\} \in M_2$ – a links subset (description operation) corresponding to the *j*-th description element the of the *i*-th functional structure.

Denotes the transition V_{ijl} from the functional unit with the descriptive element Oe_{ij} and the number N_{ij}, to the functional unit with the number L_{ijl};

η_{ij} – number of transitions types corresponding to the *j*-th descriptive element of the *i*-th functional structure;

Oee_i – description element of the equivalent functional unit of the *i*-th functional structure;

$\{y_{im}\}$ – *m*-th the valuation operation of the *i*-th functional structure used to determine the *m*-th quality index of equivalent TFU, $\{y_{im}\} \in M_4$;

z_i – evaluation operations number of the *i*-th functional structure.

Using a functional structure model (formula 4) defined in general form as well as the descriptive estimated elements and elements of the task of descriptive operations defined above, we give description of the functional structures (TFS models examples are in Table VI).

TABLE VI. EXAMPLES OF THE FUNCTIONAL STRUCTURES DESCRIPTION

TFS number	TFS designation	TFS model
1	$Fs_{RR}{}^{a}$	Fs_{RR} =<{R,1,(1,2)},{R,2,(1,3)},..., {R,n,(1,n+1)},R,{B,MT,DT}>
2	$Fs_{RK}{}^{b}$	Fs_{RK} =<{R,1,(1,2)},{K,2,(1,3),(2,1)}, R,{B,M_T,D_T}>
3	$Fs_{CRF}{}^{c}$	Fs_{CRF} =<{R,1,(1,2)},{C_F,2,(4,1),(5,3),k_c}, R,{B,M_T,D_T}>

Fs_{RR} – consistent execution of work operations.

Fs_{RK} – cyclic FN "Working operation with monitoring operation without limit on the number of cycles".

Fs_{CRF} – *n*-fold repetition of the work operation with acceptance for all successful outcomes

H. FN model of operator activity algorithm

Taking into account the description elements and description operations introduced in the models (3) and (4), the structural formula (1) of the functional network representation by elements of the sets M_1 and M_2 will look like:

$$O_{FS} ::=< \{o_{e_j}, te_j, N_j, \{V_{j_l}, L_{j_l}\} \Big| l=1,2,...,\eta_j, [k_{c_j}]\} \Big| j=1,2,...,n>, \quad (5)$$

where: Oe_j – *j*-th element of the description in the structure of the activity algorithm;

te_j – the designation in the algorithm structure of the functional unit with the description element Oe_j;

n – the number of the description elements in the algorithm structure;

$\{N_j, \{V_{jl}, L_{jl}\}$ – descriptive operation corresponding to the *j*-th element of the functional network description. It denotes the type - V_{jl} transition from the functional unit to the description element Oe_j and the number N_j, to the functional unit with the number L_{jl};

η_j – transition types number corresponding to the *j*-th description element;

k_{cj} – restriction on the repetitions number in a cycle.

I. Application in practice of mathematical models. Computer system for assessing the reliability of man-machine interaction.

The description models for human interaction with the machine were used as the basis of the language, which is a means of entering information into a computer. Based on this language, we have developed a computer system [25] that provides:

- convenient input of information:
- automatic structural analysis of man-machine interaction algorithms and the selection of all TFS;
- automatic assessment of the reliability and timing of the implementation of control algorithms;

- man-machine interaction optimization.

An example of recognition of TFS, reduction and reliability assessment is shown in Fig.1. The description of the functional network that provides automatic reduction (according to (5)) can be specified as:

O_{FS}=<{S,S,1,(1,2)}, {R,P1,2,(1,3},{R,P2,3,(1,4)},

{K,K1,4,(1,6),(2,5)},{R,P3,5,(1,3)},{R,P4,6,(1,7)}

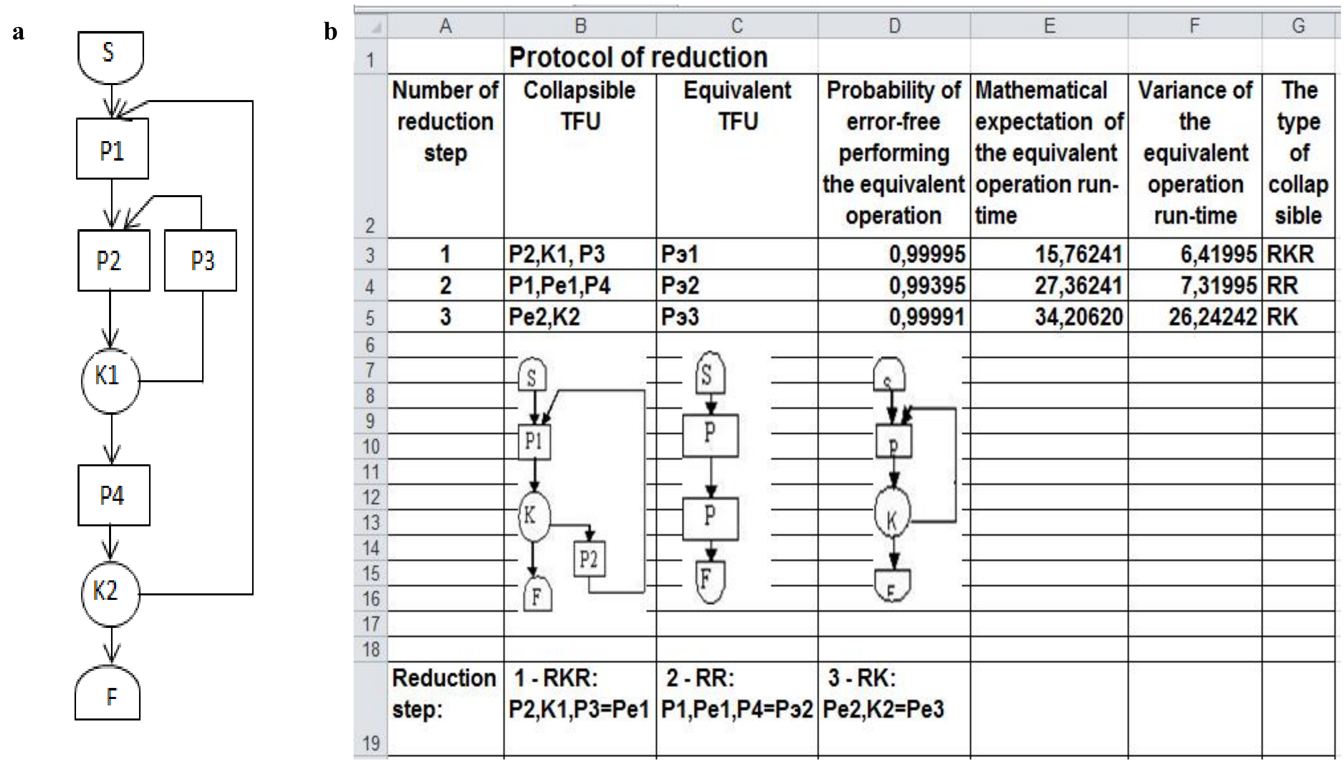
{K,K2,7,(1,8),(2,2)}, {F,F,8}>

The computer system is used to improve the reliability of automated systems in industry [17, 25–28], agriculture [25, 27], banking management [24, 28], e-learning [20, 26]. The description of the algorithm is entered once (can be stored in a database) using the proposed language.

Recognition of TFS, reduction and evaluation is done automatically. Baseline data may change in dialogue mode. It is possible to take into account the parameters of

- a person:
    - functional state,
    - stress,
    - knowledge and skills,
    - motivation,
    - etc.,
- machine parameters,
- workplace parameters,
- environmental parameters,
- the structure of human-machine interaction.

The system allows to find ergonomic reserves to improve the efficiency of automated control and simulate problem situations.



	A	B	C	D	E	F	G
1		Protocol of reduction					
2	Number of reduction step	Collapsible TFU	Equivalent TFU	Probability of error-free performing the equivalent operation	Mathematical expectation of the equivalent operation run-time	Variance of the equivalent operation run-time	The type of collapsible
3	1	P2,K1, P3	Pэ1	0,99995	15,76241	6,41995	RKR
4	2	P1,Pe1,P4	Pэ2	0,99395	27,36241	7,31995	RR
5	3	Pe2,K2	Pэ3	0,99991	34,20620	26,24242	RK
19	Reduction step:	1 - RKR: P2,K1,P3=Pe1	2 - RR: P1,Pe1,P4=Pэ2	3 - RK: Pe2,K2=Pe3			

Fig. 1. An example (is taken from the practice of ergonomic support of call center operators (managing access to information resources) [24]). a- functional network; b- reduction protocol (prepared by computer program). 3steps for recognizing TPS are shown.

Conclusion

Human activity in computer systems is conveniently described using FN. The main problem of automating the ergonomic modeling of complex human-machine systems is the inability to automatically analyze the FN. The analysis of the FN elements was performed.

This allowed us to develop models of:

- typical functional units;
- typical functional structures;
- complete FN, which describes the activities of human-operator.

Such models represent a language for describing the algorithm of human activity, which is convenient for entering into a computer.

The language is designed in such a way that it allows you to automatically identify typical functional structures and reduce FN.

The developed models allowed us to create a computer program for assessing the reliability of the human-operator. The computer program was used in the design process for systems of various purposes and its effectiveness was shown.

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